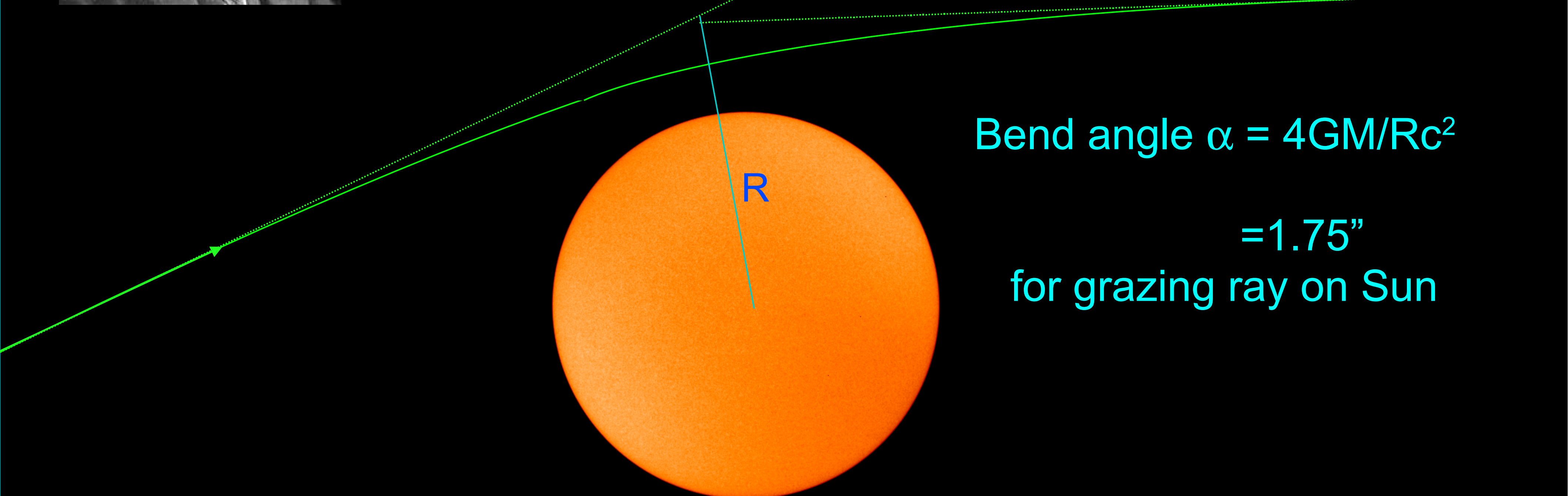
Gravitational Lenses

The First Discoveries

Summary:

- first detections of gravitational deflection of light
- some early theoretical developments
- discovery of the double and triple quasars
- a few comments on the huge progress in the area since


α
R
Bend angle α = 4GM/Rc²
=1.75”
for grazing ray on Sun

Sky needs to be dark, so have to look during a solar eclipse
and even then coronamakes it difficult

Eddington measured stellar position shifts from 1919 solar eclipse.

France 1999

Measurement errors also mean it is not easy --

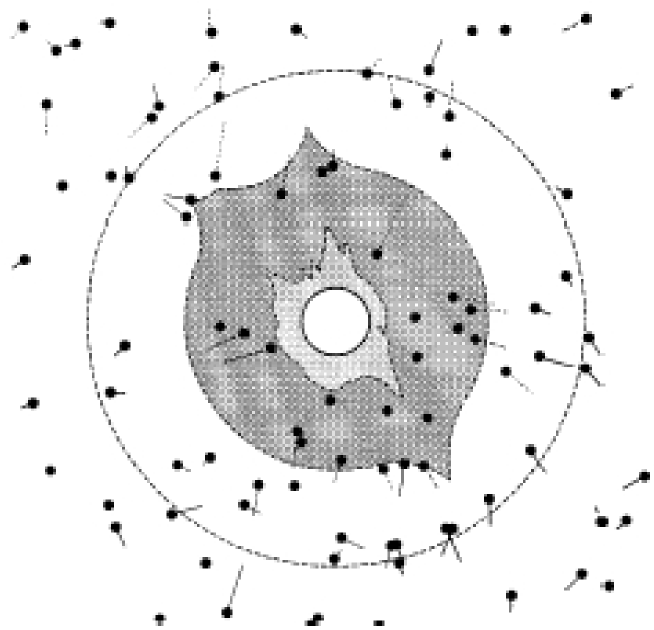


Figure 6. Changes in star positions recorded during the eclipse of 1922 and published in Campbell & Trumper (1923). The eclipsed Sun is represented by the circle in the centre of the diagram, surrounded by a representation of the coronal light. Images too close to the corona cannot be used. The recorded displacements of other stars are represented by lines (not to scale)

But Eddington's results suggested Einstein was close to reality.

Then nothing much happened for several years, until
Sjur Refsdal looked at possibilities on a much larger scale.

The gravitational lens effect 1964, MNRAS, 128, 295
- multiple images, light amplification, image shapes

On the possibility of determining Hubble's parameter and the masses of galaxies from the gravitational lens effect 1964, MNRAS, 128, 307
- time delay from e.g. a lensed supernova

On the possibility of testing cosmological theories from the gravitational lens effect 1966, MNRAS, 132, 101
- time delays to estimate deceleration parameter, density parameter (and so ρ, Λ)

On the possibility of determining the distances and masses of stars from the gravitational lens effect
1966, MNRAS, 134, 315
- needs two widely separated observers

The first of these was the landmark paper. It showed the familiar lens geometry, with two images..

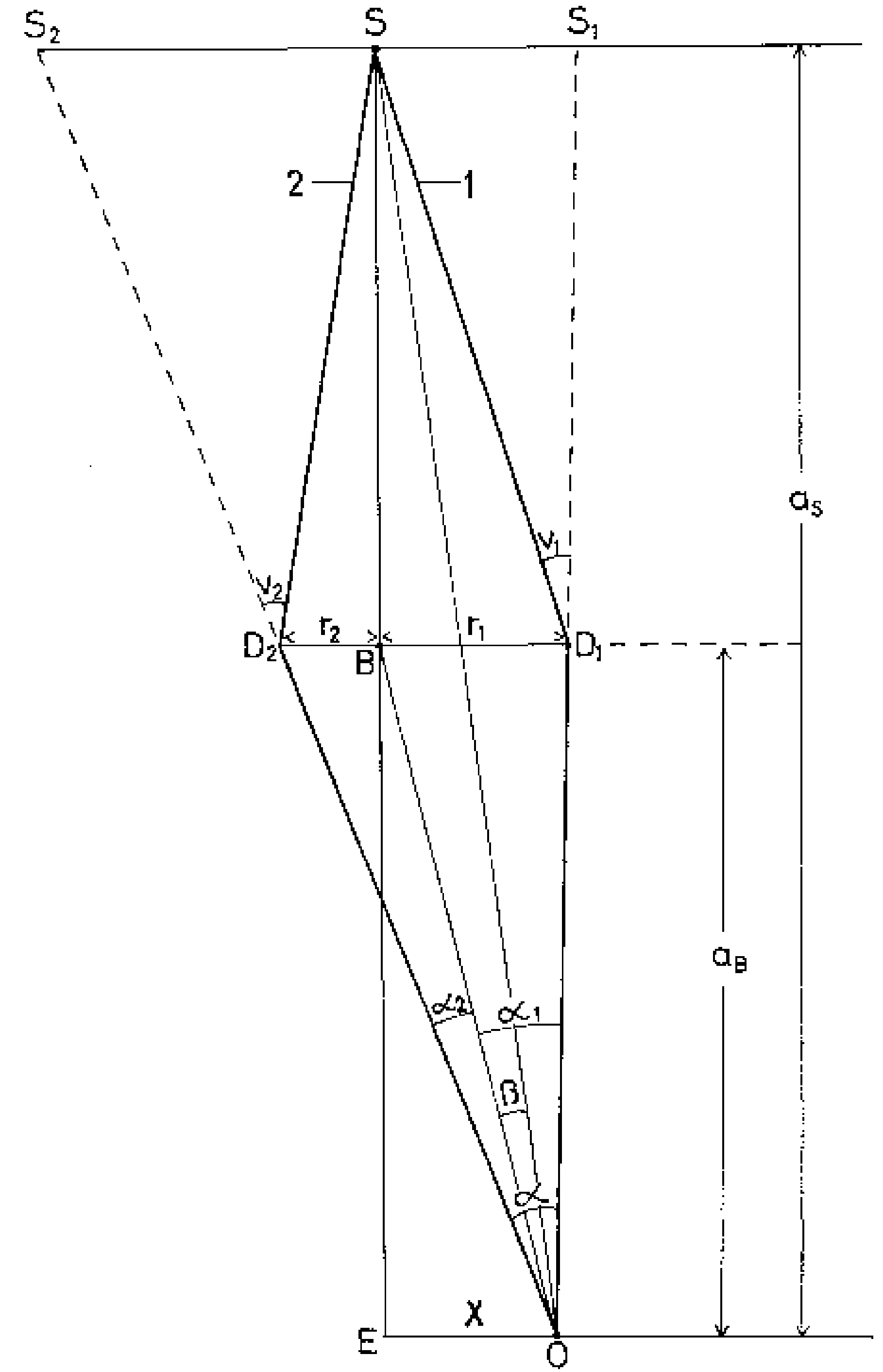


FIG. 1.—*The two light rays from S to O.*

and then by ray-tracing ..

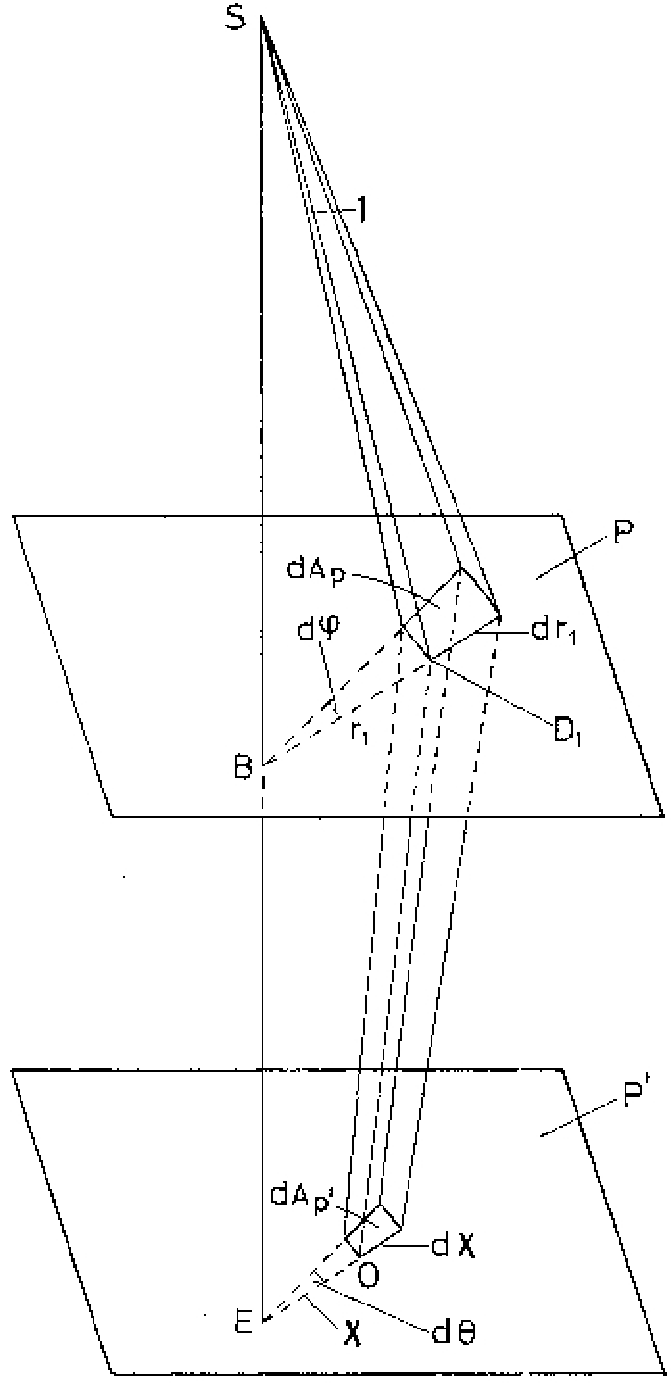


FIG. 2.—A bundle of rays from S, passing close to O.

arrive at the image shape and amplification factor.

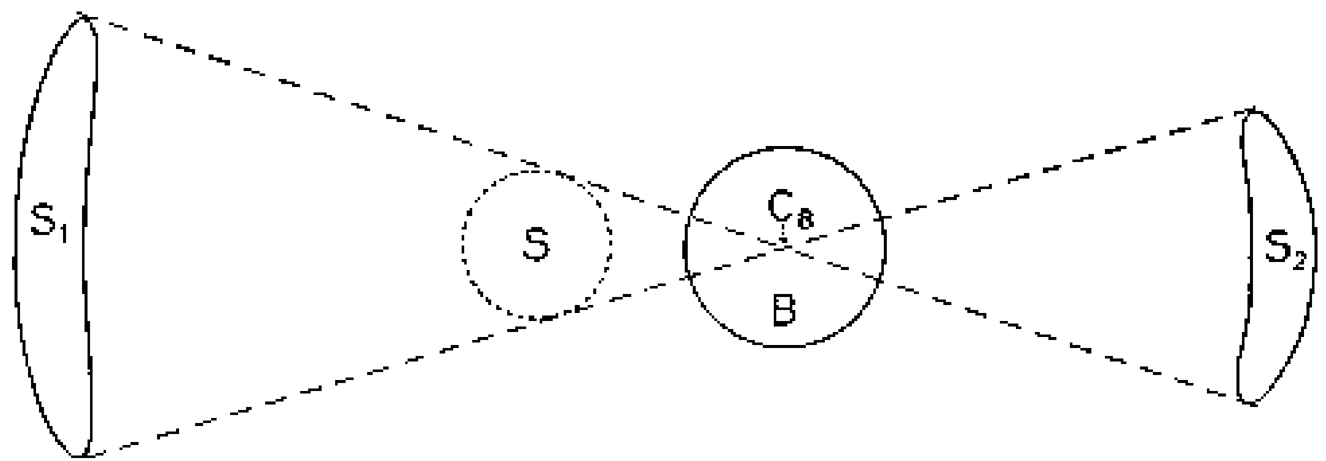


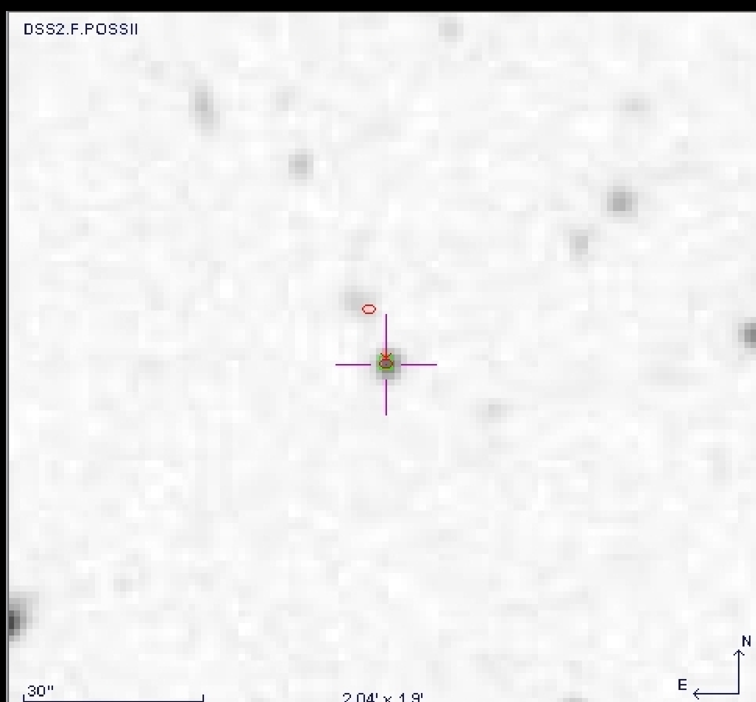
FIG. 3.—*The shape and position of S_1 and S_2.*

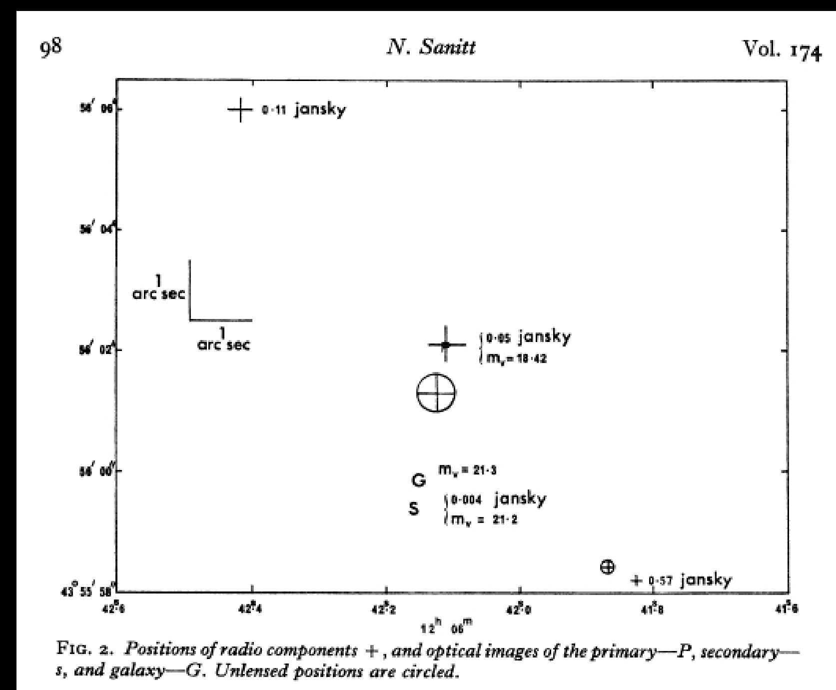
.. which left me with the impression that the signature of gravitational lensing was effectively little bananas on the sky.

Not very intensive searches for lensed objects followed, without much success:

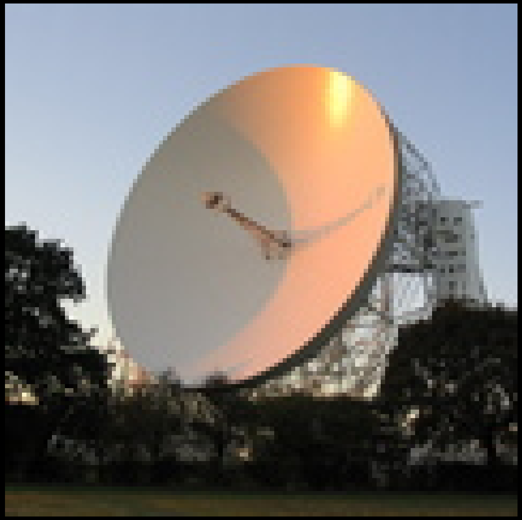
Nigel Sanitt: *3C 268.4 - Evidence for the presence of a gravitationally-lensed secondary image* MNRAS, 174, 91, 1976.

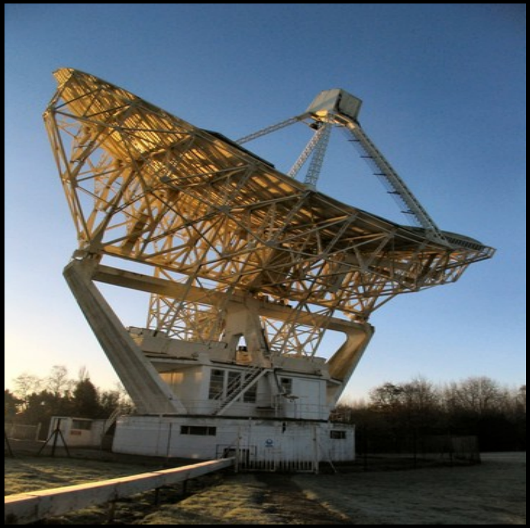
This vanished into obscurity, probably because it wasn't demonstrably a lens.





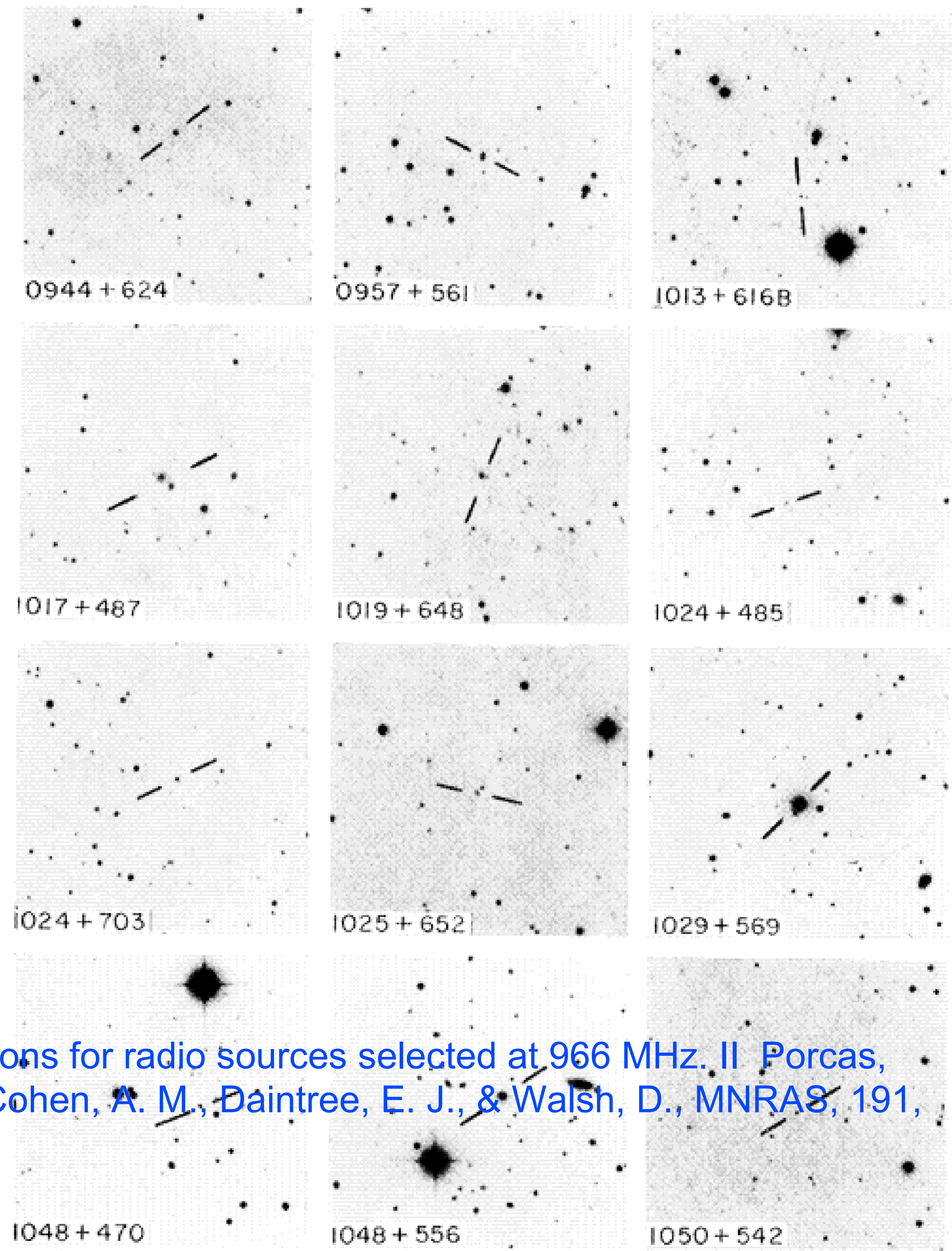
This changed in 1979, as a result of routine
optical observations to confirm quasar candidates
from a 966MHz Jodrell Bank radio survey undertaken
by Dennis Walsh and collaborators.
It was one of the first surveys for which accurate positions
were obtained - to within about 2” for unresolved sources -
using the MkIA-MkII interferometer.





MkIa/MkII error 6x11"
A-15.4 +11.9arcsec
B-14.2 +5.9
.. so outside tolerance,
but both objects very blue

8.5arcmin finding charts



Radio positions and optical identifications for radio sources selected at 966 MHz. II Porcas, R. W., Urry, C. M., Browne, I. W. A., Cohen, A. M., Daintree, E. J., & Walsh, D., MNRAS, 191, 607, 1980.

Part of this was because 0957+561 was not unresolved - later observations showed quite complex structure

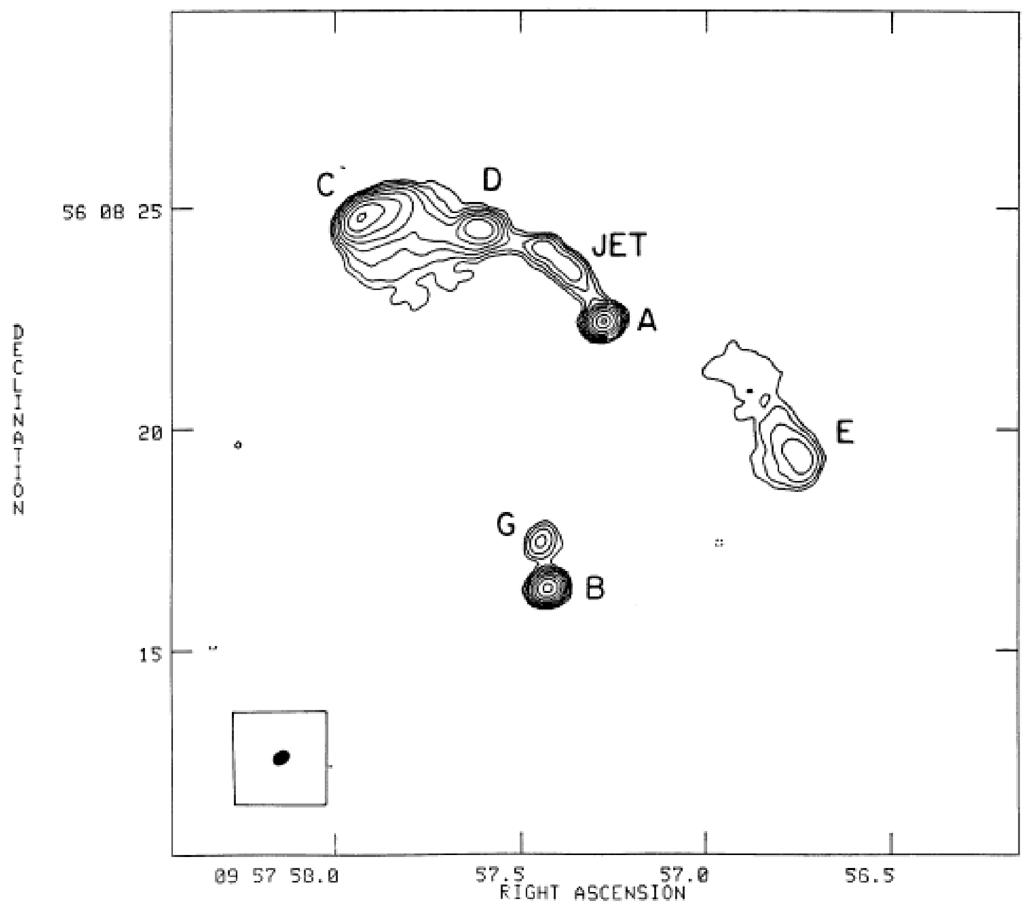


FIG. 1.—Self-calibrated 6 cm VLA map of the double quasar 0957 + 561, epoch 1980 December 16. The map has been restored with an ellipsoidal Gaussian clean beam with full-width at half-maximum of 0".40 × 0".35 at position angle 120°, corresponding to the true resolution of the observation, as shown in the box in the corner. Contour levels are −0.5, 0.5, 1, 2, 4, 8, 16, 32, 64, and 95% of the peak brightness (at A) of 33.3 mJy per beam area.

Roberts et al, ApJ, 293, 356, 1985

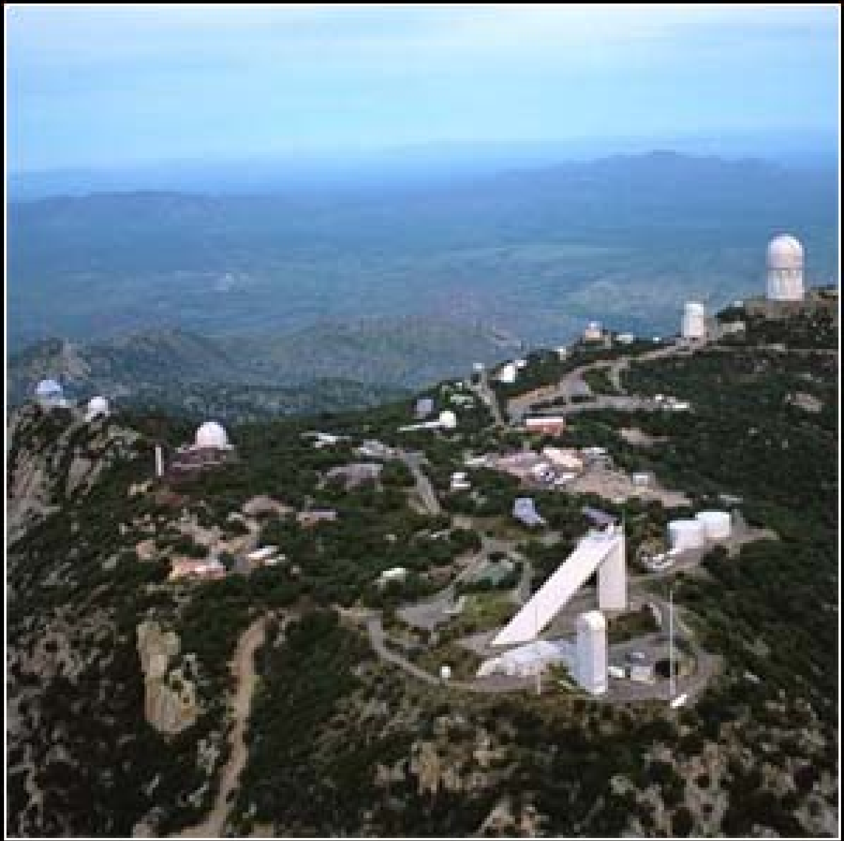
Dennis Walsh's identification programme for these Jodrell Bank radio source quasar candidates was their spectroscopic confirmation.

This involved several telescopes, and people:

U Texas, with Derek & Bev Wills (several runs)

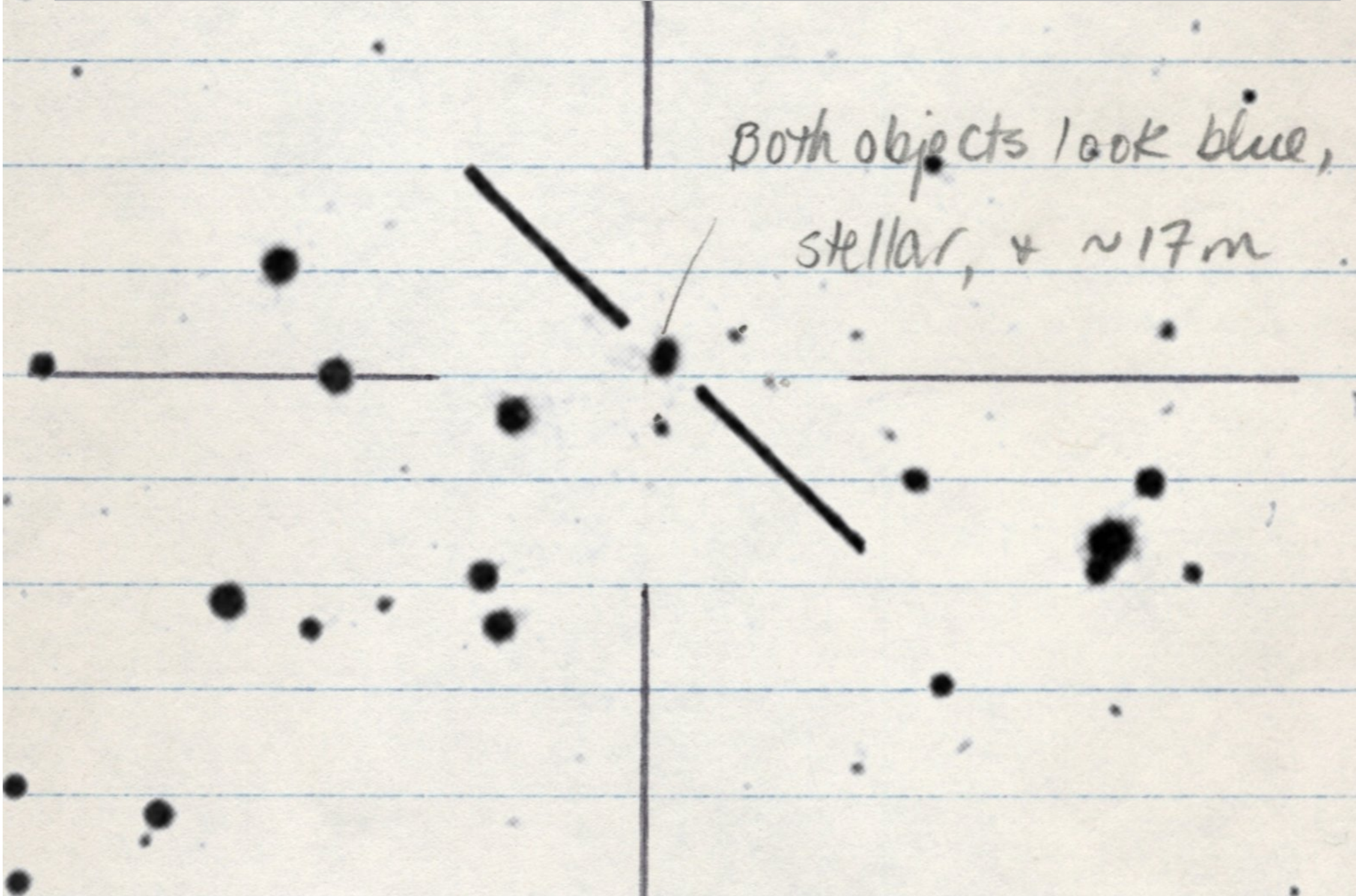
Palomar, with Maarten Schmidt, Alec Boksenberg and me

Kitt Peak, with me



..and I was the lucky one

Discovery of the first gravitationally lensed quasar came about in the usual way - total serendipity.



Dennis & I were awarded time on the Kitt Peak 2.1m for spectroscopy of quasar candidates from the survey..

.. on the first night we took spectra of both objects (a practice established on a previous run where a star was close to a quasar on the sky), and found:

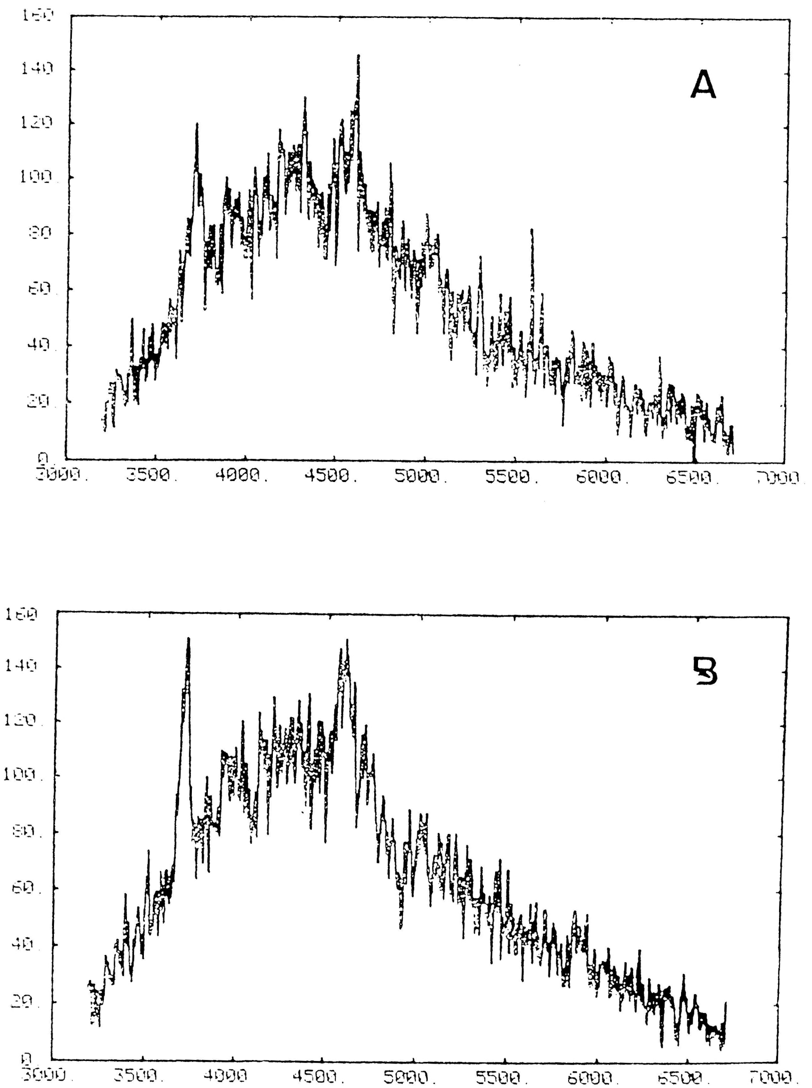


Fig. 5. Upper: First spectrum obtained for 0957+561A at the 2.1-meter telescope, 29 March 1979. Lower: First spectrum obtained for 0957+561B, a few minutes later.

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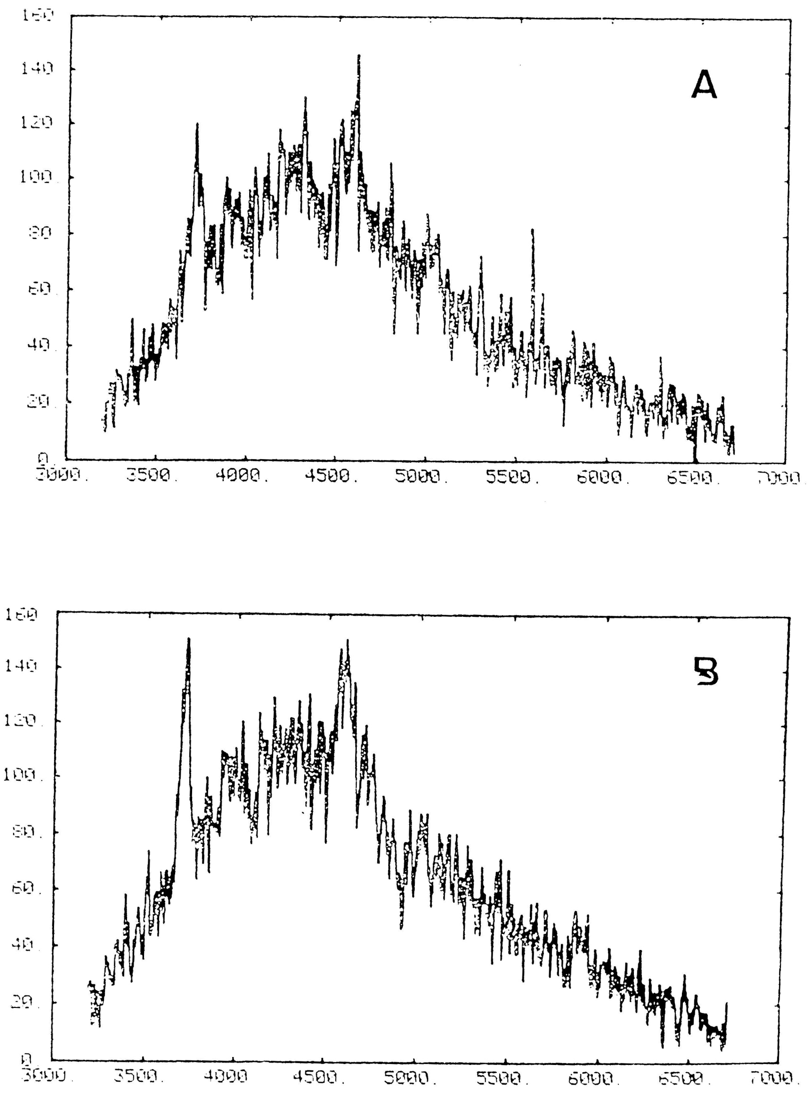


Fig. 5. Upper: First spectrum obtained for 0957+561A at the 2.1-meter telescope, 29 March 1979. Lower: First spectrum obtained for 0957+561B, a few minutes later.

So we asked the telescope operator (as politely as we could) if she had *really* moved the telescope..

.. and other checks were made.

Result was reduced spectra which look amazingly similar.

Some worries over excess in ‘b’ which we guessed (wrongly) might be dust extinction differences at the quasar redshift. S/N in that region pretty poor, and vague calibration worries meant we were not too concerned.

z_{em}=1.414

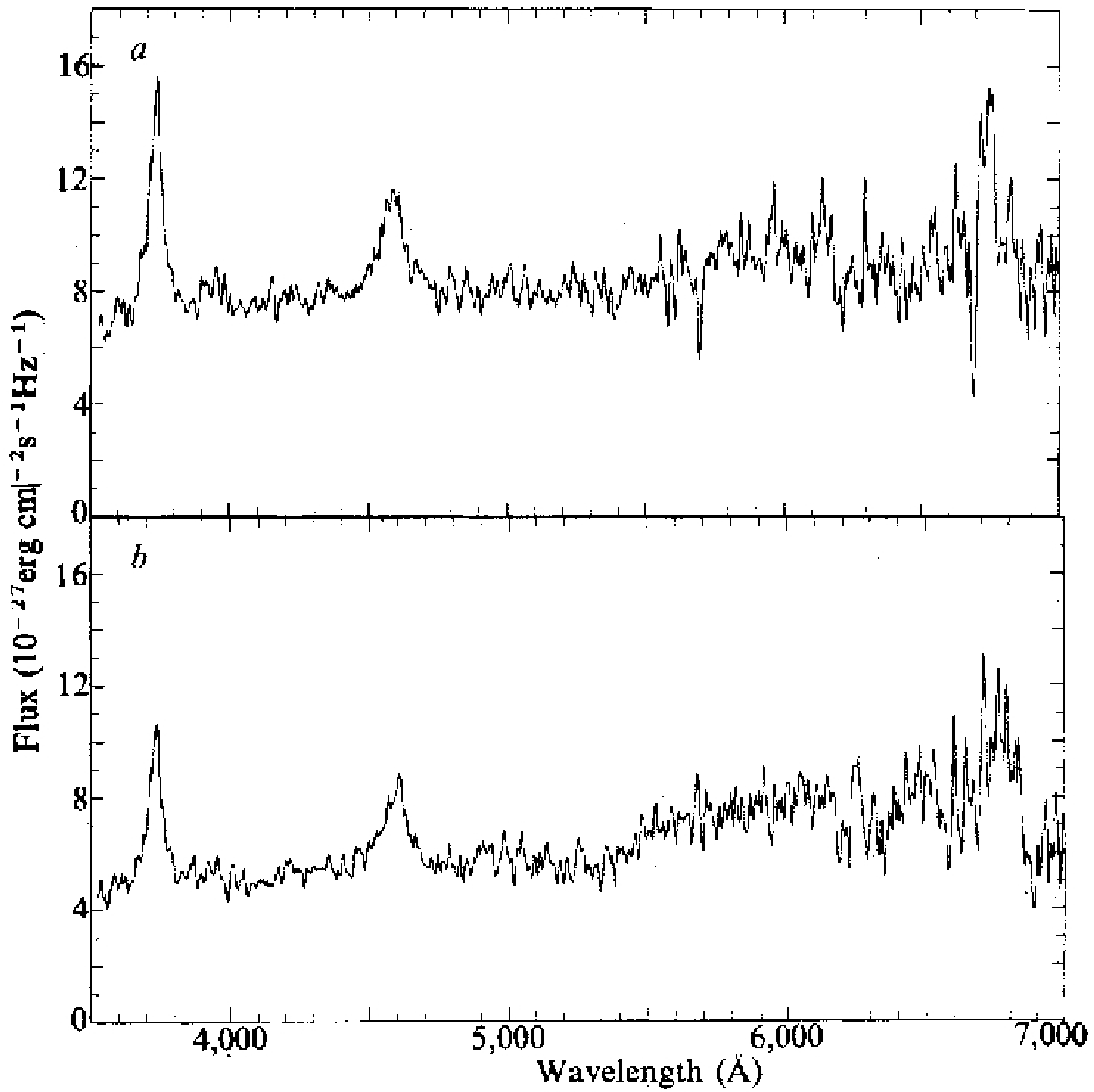


Fig. 2 IIDS scans of 0957+561 A(*a*) and B(*b*).
The data are smoothed over 10 Å and the spectral resolution is 16 Å.

One compelling pointer toward a lens came from Ray Weymann's higher resolution spectrum, taken the next night, which showed identical absorption lines near the quasar redshift, and we could not see that over several 10s of kpc (on a twin QSO interpretation) they should be so similar.

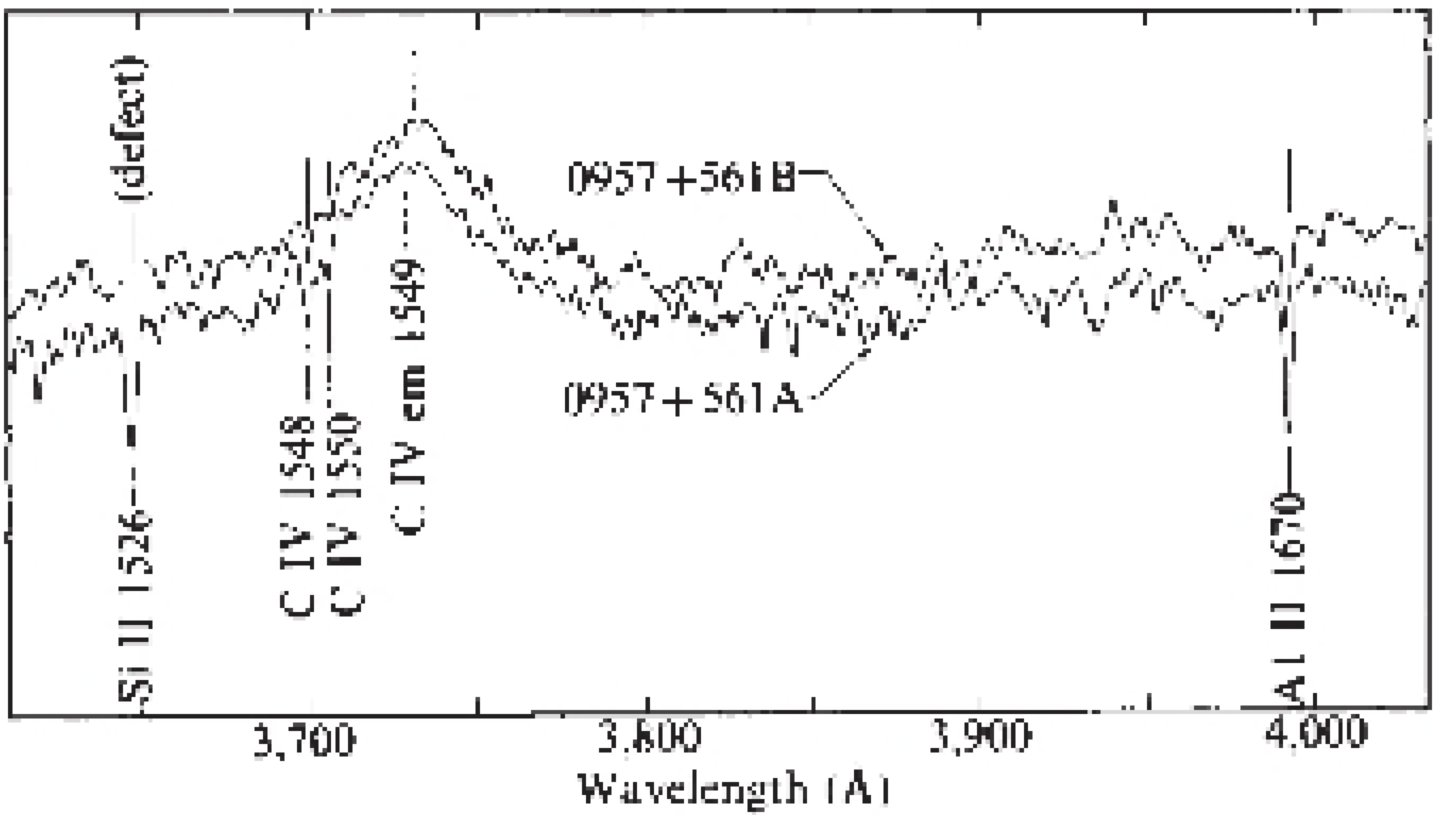
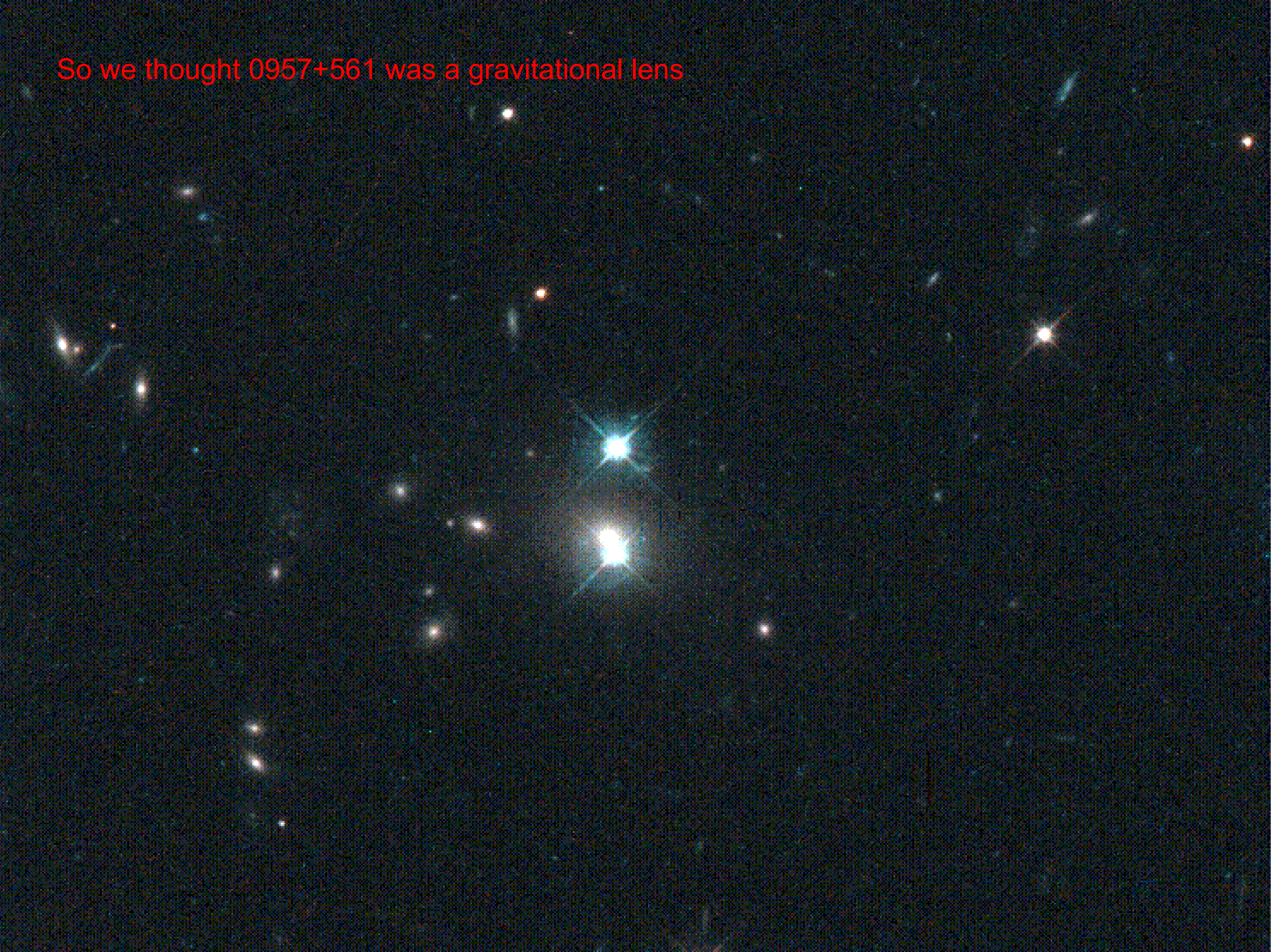
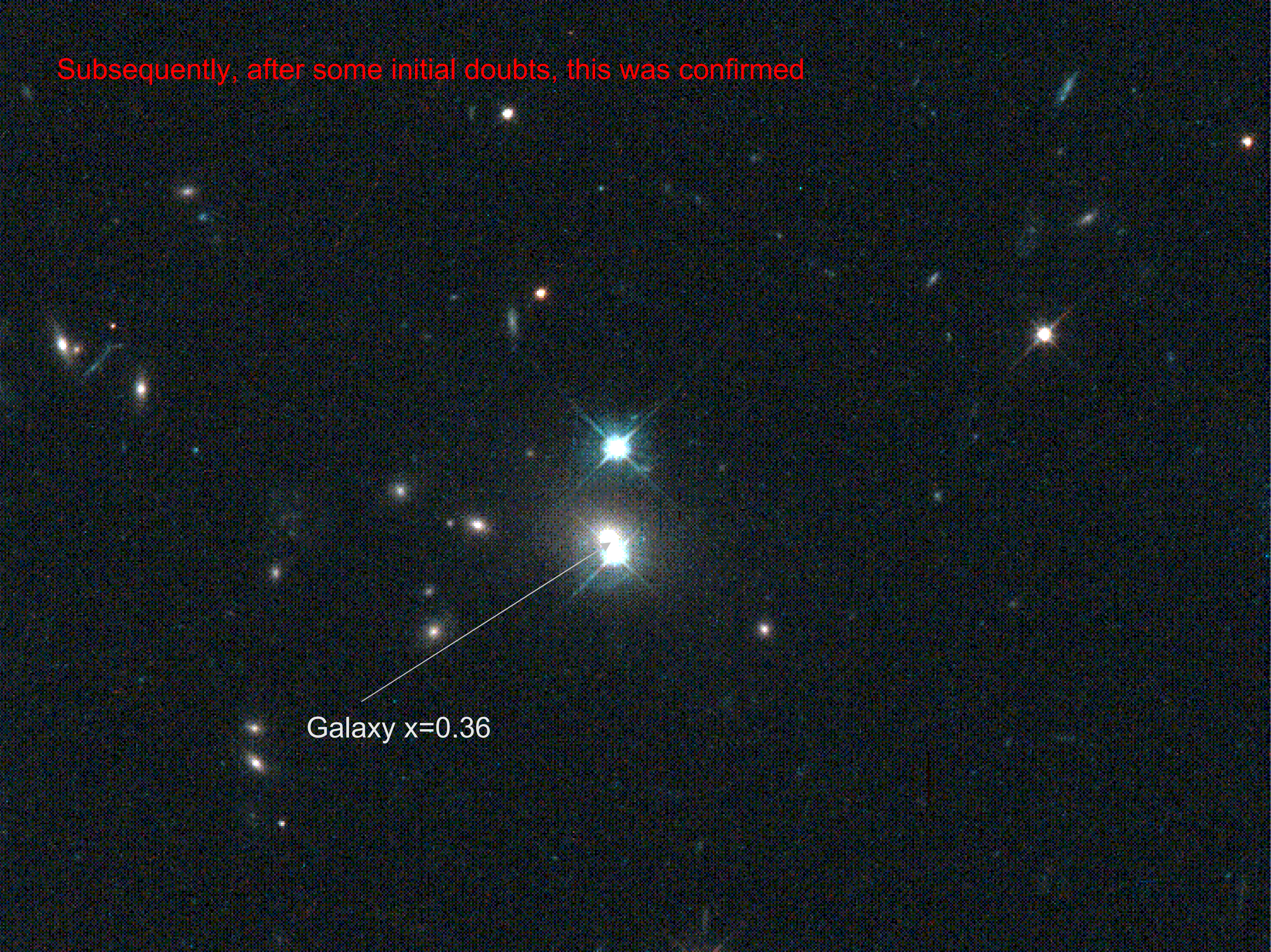
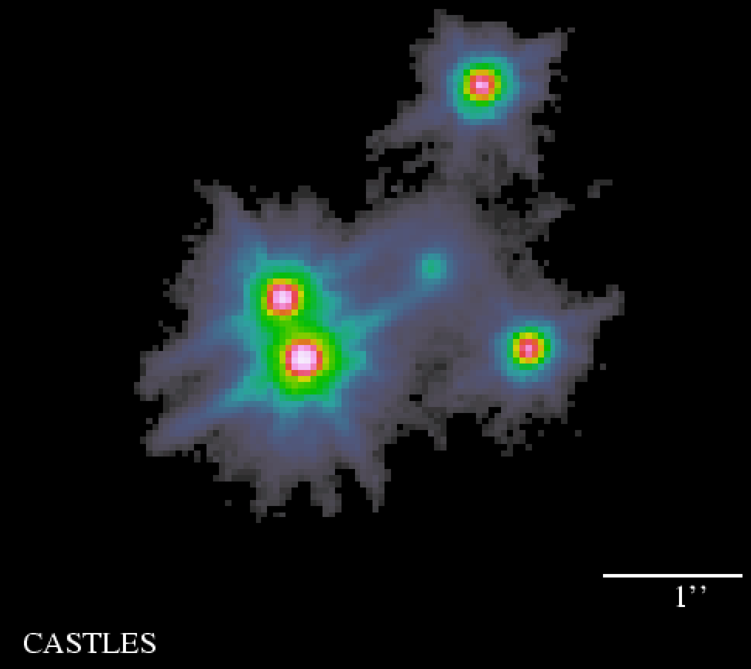


Fig. 3 Microdensitometer tracings of portions of the spectra of 0957+561 A and B. Original dispersion of the plates was 47 Å mm^{-1}. The solid lines mark the position of absorption features in the two QSOs and the dashed lines mark the adopted centres of the C IV emission line.


So we thought 0957+561 was a gravitational lens

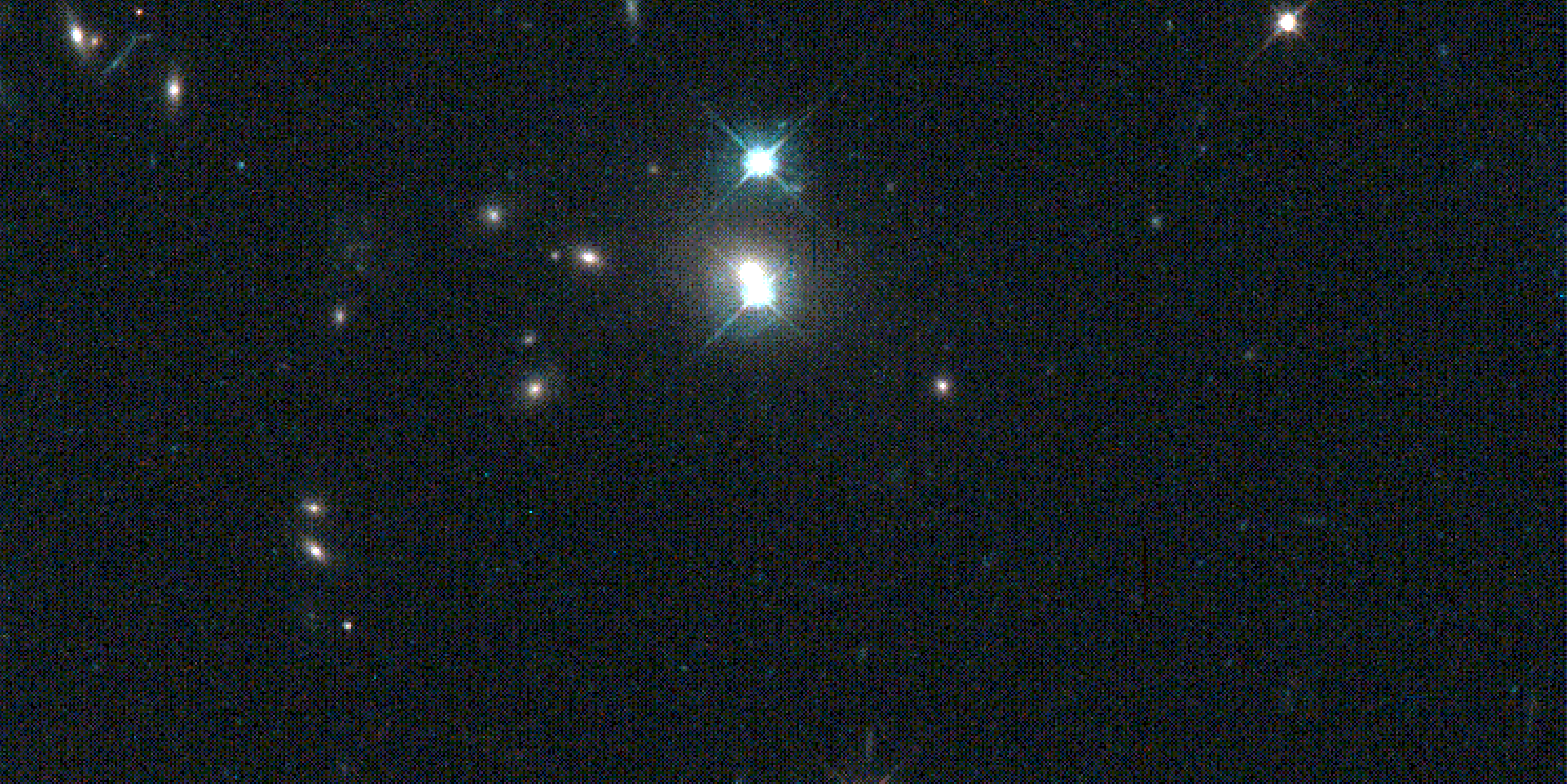

Subsequently, after some initial doubts, this was confirmed
Galaxy x=0.36

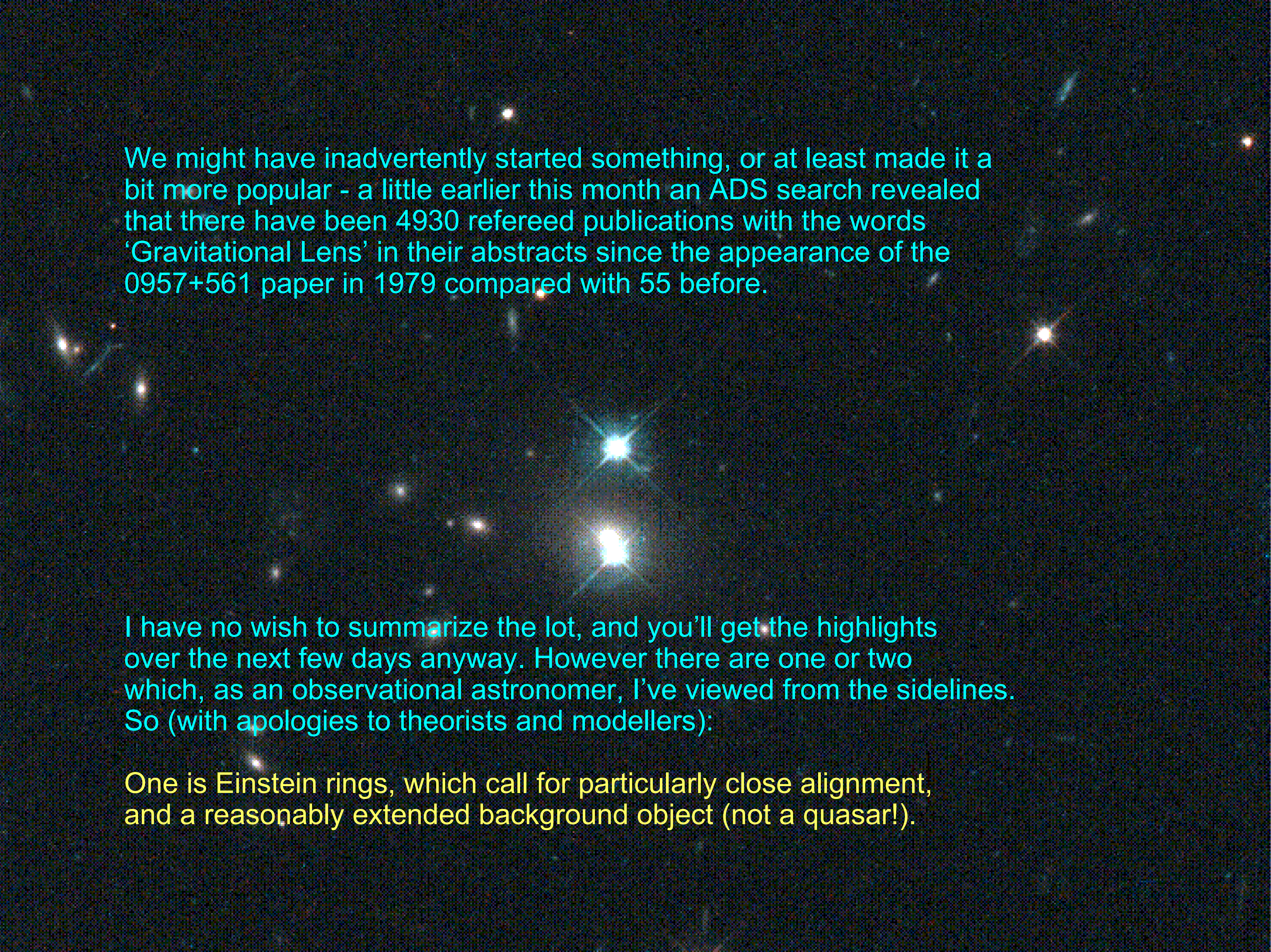
Once first found others followed quite quickly - next one a year later PG1115+080, from the MMT (Weymann et al, Nature, 285, 641, 1980)



There are 4 bright images (plus one faint) because the galaxy is not spherical. Optically: ‘triple quasar’.

We might have inadvertently started something, or at least made it a bit more popular - a little earlier this month an ADS search revealed that there have been 4930 refereed publications with the words ‘Gravitational Lens’ in their abstracts since the appearance of the 0957+561 paper in 1979 compared with 55 before.





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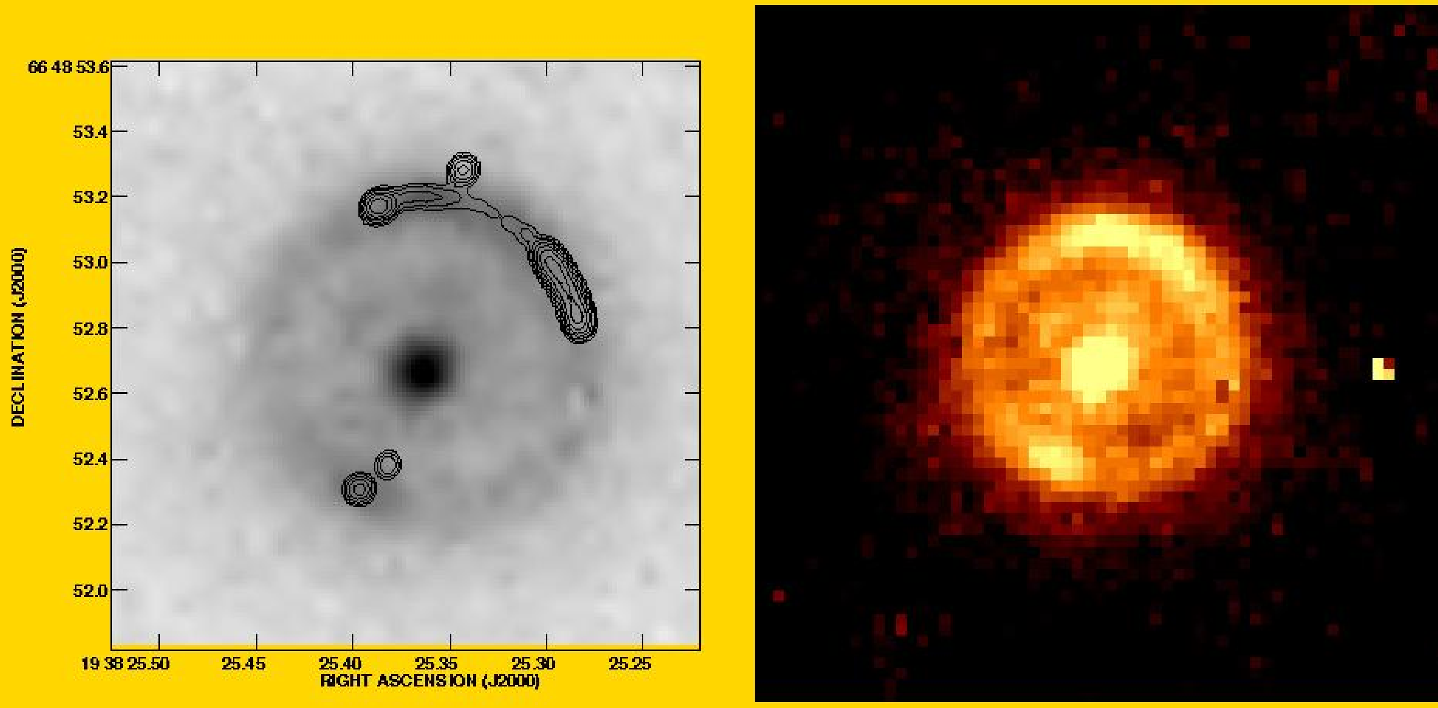
I have no wish to summarize the lot, and you'll get the highlights over the next few days anyway. However there are one or two which, as an observational astronomer, I've viewed from the sidelines. So (with apologies to theorists and modellers):

One is Einstein rings, which call for particularly close alignment, and a reasonably extended background object (not a quasar!).

What the images of extended sources (e.g. galaxies, extended radio sources) look like depends on their angular separation from the centre of the lens:

Images are a bit narrower radially, and outer one is always larger tangentially.


Early example: Warren et al, MNRAS, 278, 1996
This one: Cabanac et al, A&A, 436, 21, 2005

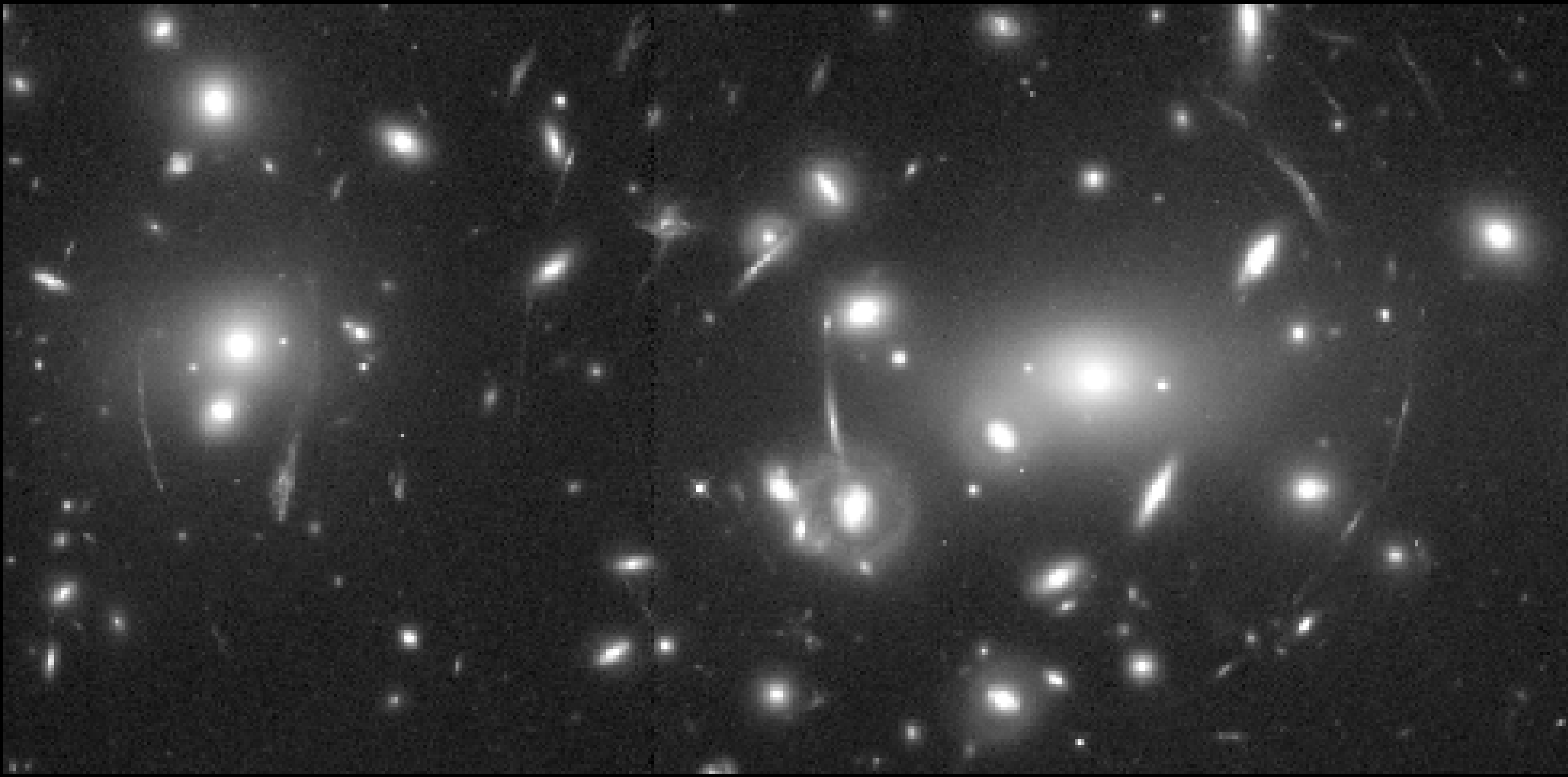


The gravitational lens JVAS B1938+666

Left: HST/NICMOS greyscale with MERLIN radio contours
Right: Colour image of the HST/NICMOS image

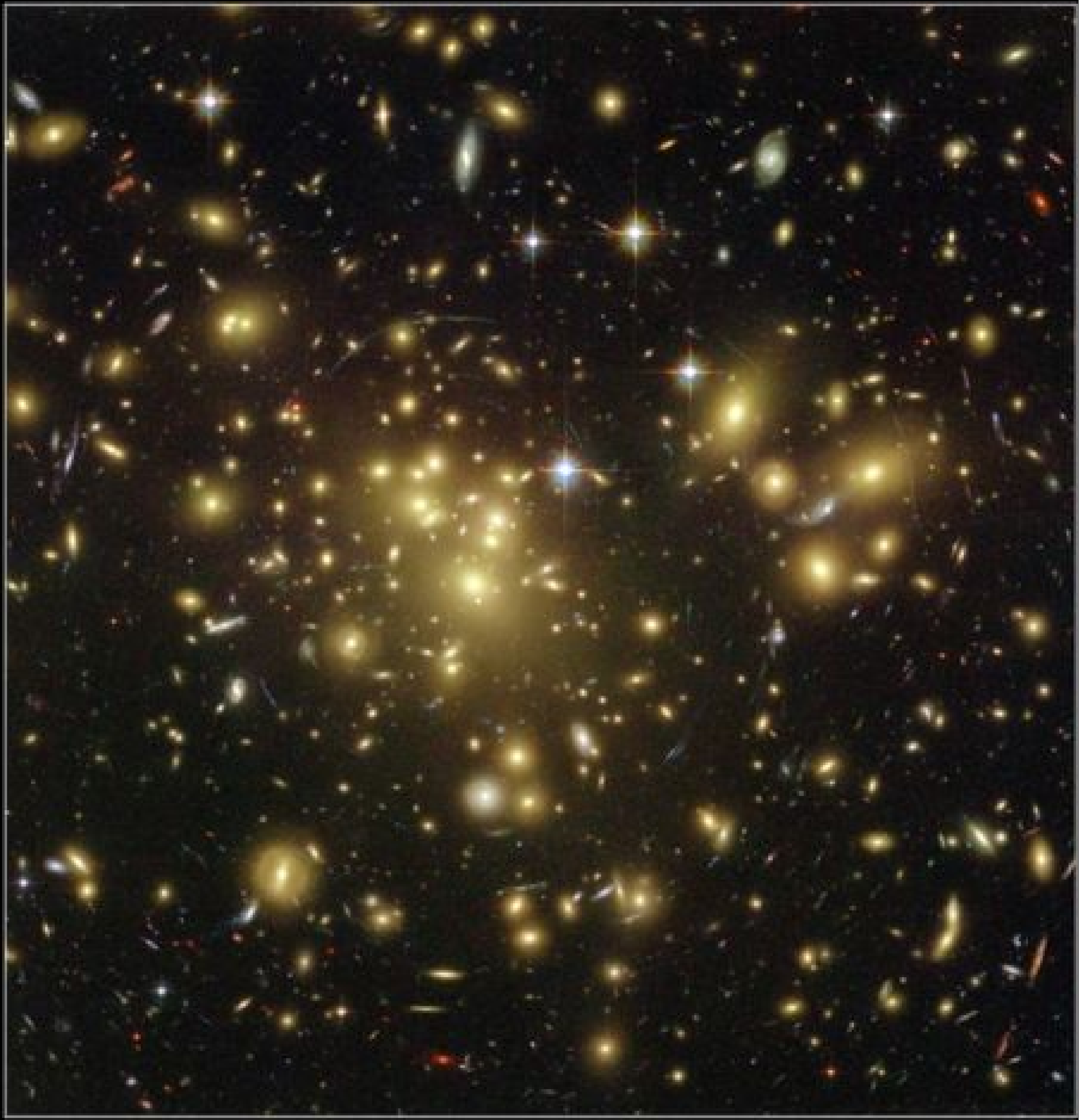
King et al. MNRAS, 295, L41, 1998

Abell 2218 – a classic example of lensed galaxies



W Couch (Swinburne)

For less extreme distortions
mass distribution
can be inferred
- there are often lots of
background galaxies
(weak lensing)



Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

Bullet cluster

A composite image of two colliding galaxy clusters showing hot gas (X-ray image, pink) and galaxies (optical image, orange & white). About 90% of the normal (i.e. baryonic) matter is in the hot gas, while weak gravitational lensing of background galaxies shows that most of the mass is in the regions shown in blue. This provides direct evidence that over 70% of the matter in the clusters is dark.

Now I look forward to hearing about theoretical developments, microlensing, galaxy strong lensing, lensing surveys, weak and cluster lensing...